EVALUATION OF DISCRETE ACTUATORS FOR THE REGULATION OF CONSTANT-SPEED HAWTS

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ABSTRACT

A wide range of factors influence the design of the blade servo system for a pitch regulated constant speed wind turbine. One design option is to dispense with continuous actuator operation and employ an intermittently acting actuation system which is capable of moving the blades only at specific velocities. In this paper, generic discrete actuator configurations are considered from the viewpoint of their influence upon the design and performance of the controller for a two-bladed pitch-regulated constant-speed grid-connected HAWT representative of commercial machines in its class.

1. INTRODUCTION

A wide range of factors influence the design of the blade servo system for a pitch regulated constant speed wind turbine. One design option is to dispense with continuous actuator operation and employ an intermittently acting actuation system which is capable of moving the blades only at specific velocities (see, for example, Agius *et al.* 1993). In this paper, generic discrete actuator configurations are considered from the viewpoint of their influence upon the design and performance of the controller for a two-bladed pitch-regulated constant-speed grid-connected 300 kW HAWT representative of commercial machines in its class.

2. PRELIMINARIES

The combined dynamics of the drive-train, generator and power transducer are essentially linear and, together, are modelled by the transfer function

$$\frac{46460.9}{s^5+81.27s^4+3683.90s^3+120773.6s^2+1474504.0s+36857450}$$

The aerodynamic behaviour of wind turbine blades is highly nonlinear and strongly dependent on wind speed. It is standard practice for wind turbine controllers to include a nonlinear gain to compensate for this variation and make the control task essentially linear (Leith & Leithead 1997). However, the representation of the aerodynamics is very basic and subject to considerable uncertainty. Consequently, a good gain margin, in conjunction with a good phase margin, is particularly important in order to achieve adequate stability margins. Because of the complexity of the interaction of the rotor with the wind, it is not possible to quantify the uncertainty in the aerodynamic gain but practical experience indicates that 10 dB is an appropriate gain margin (Leithead *et al.* 1991). If adequate gain and phase margins are not achieved the system must sometimes destabilise, although not necessarily become unstable, in which case the wind turbine would experience large load fluctuations. To ensure a fair comparison, all of the controllers are designed to have a gain margin of at least 10 dB and a phase margin of approximately 60 degrees.

A turbine configuration with a continuous actuation system is employed as a benchmark against which to assess the impact of adopting an actuator with discrete action. The dynamics of the continuous actuator are modelled by the transfer function 20.7/(s+20.7). An analogue anti-aliasing filter, with transfer function $2209/(s^2+65.8s+2209)$, is positioned at the input to the actuator. Servo pitch acceleration provides a measure of the force or torque developed by the actuator and the standard deviation reflects activity over the medium and long term. For the machine considered here, the continuous actuator is an electro-mechanical system and there exists a restriction of around 20 deg/s^2 on the permitted servo pitch acceleration, equivalent to a restriction on the servo motor current, which is imposed to prevent over-heating. The controllers considered here are all designed to satisfy this requirement.

Three different control strategies are considered. The first control strategy is a conventional linear controller. The performance of this controller is indicative of the best performance that may be achieved by linear control within the specifications. The transfer function of the linear controller is

$$\frac{0.394\,(s+1.6)^2(s^2+7.243s+38.637)(s^2+1.5s+104.04)(s^2+6s+416.16)}{s(s+0.3)(s+3.7)(s+20)(s+50)(s^2+11s+104.04)(s^2+10s+416.16)}$$

(Gain margin 10 dB, phase margin 56.14 degrees, cross-over frequency 1.826 r/s. This controller is similar to previous controllers used with a commercial two-bladed design of wind turbine and includes low frequency shaping, high frequency roll-off, and notches at 2P and 4P (Leithead *et al.* 1991)).

The second control strategy is a high-performance dual-mode approach (Leith & Leithead 1996). This control strategy is based on the observation that, owing to the nonlinear behaviour of the rotor, the demand which a linear controller places on an actuator decreases with rising wind speed. It does so rapidly in lower wind speeds below 15 m/s but much less rapidly in higher wind speeds above 18 m/s. However, it is at these higher wind speeds that controller performance is most critical. These considerations suggest than the appropriate wind speed at which to switch between the two controllers lies between 15 m/s and 18 m/s. A wind speed of 16 m/s (corresponding to 11.14 degrees pitch demand) is selected as the switching point. The foregoing conventional design of linear controller is used in wind speeds below this threshold and a more active linear controller is employed at higher wind speeds; the more active controller has transfer function

$$\frac{2.53\,(s+1.7)(s+1.8)(s^2+3s+416.16)\,(s^2+7.59s+68.06)}{s(s+0.3)(s+3.7)(s^2+8s+416.16)\,(s^2+14.67s+100)\,(s+30)} \quad \frac{}{(s^2+2s+104.04)(s^2+7.243s+38.637)} \quad \frac{}{(s^2+11s+104.04)(s+100)}$$

(gain margin 10 dB, phase margin 55.62 degrees, open-loop cross-over frequency 2.85 r/s). In order to ensure smooth switching between the low and high wind speed controller, minor feedback loops are employed which ensure that, while only one controller acts on the plant at any time, both controllers are both continuously driven by the same input. Switching transients associated with the low frequency controller dynamics are thereby avoided. In addition, the pure integration term, which is common to both the high and low wind speed controllers, is located after the other controller dynamics with the switch positioned immediately prior to it. Owing to the switch, the input to the integrator may be discontinuous. However, for an input with finite magnitude (that is, the system is stable), the output of the integrator is continuous. Extensive simulations confirm that these simple techniques are extremely effective in preventing unacceptable switching transients. Moreover, the integrator acts to smooth any chatter of the switch. The realisation adopted therefore provides an elegant alternative to the more conventional solution of introducing hysteresis.

The third control strategy is to augment the foregoing dual-mode strategy to respond directly to peaks in the generated power (Leith & Leithead 1995). Often, it is possible to intermittently demand a high level of actuator activity for short periods, operating the actuator at its hard velocity and/or acceleration constraints. This can be exploited to improve the response to the worst peaks in the power output by operating the actuator temporarily at its maximum level when the start of an unacceptably high peak in the power output is detected, therefore responding as rapidly as possible to the disturbance. Details of the application of this approach to augment the dual-mode strategy are presented in Leith & Leithead (1995)

3. DISCRETE ACTUATOR CONFIGURATIONS

The discrete actuator configurations considered are depicted in figure 1; these are not detailed designs but rather generic representations for the purpose of control analysis. A simple representation of the servo dynamics is employed and a comprehensive analysis is not attempted. The dynamic behaviour of the actuator is modelled by a simple transfer function consisting of an integrator and a first-order lag (see, for example, Merrit 1967). The specific discrete nonlinearity considered corresponds to moving the blades at velocities of 0 deg/s, ±2 deg/s, ±5 deg/s and ±15 deg/s; these values were chosen to achieve good performance but are not optimal. The actuator of figure 1a is a velocity demand configuration whilst that of figure 1b employs additional feedback to obtain a position demand configuration.

In each case, the impact of the actuator nonlinearity upon the stability and robustness of the control loop may be assessed in a straightforward, albeit approximate, manner by describing function analysis (Atherton 1982). (If required, rigorous, but more conservative, results may be obtained by employing small gain methods (see, for example, Leith & Leithead 1997)). By removing the pure integral action (since this is now provided by the actuator itself), modifying the remaining controller transfer function to include an additional lead/lag term $1.20(s+2.066)/(s+2.48)$ and employing a new analogue filter with transfer function $900/(s^2+36s+900)$, the open-loop transfer function of the turbine with the actuator of figure 1a, modified such that the nonlinearity is replaced by a unity gain, is essentially unchanged from the continuous actuator configuration described in section 2. Hence, since the describing function of the actuator nonlinearity is purely real with magnitude less than unity (Atherton 1982) it follows immediately that the controllers designed for the continuous actuator configuration may also be applied with the discrete actuator (provided the foregoing modifications are carried out) and the stability margins of these controllers are indicated to be approximately preserved with this configuration of discrete actuator.

In section 2, it is noted that, in order to prevent overhearing, there exists a restriction on the maximum allowable standard deviation of the pitch acceleration when an electro-mechanical configuration is employed for the continuous actuation system. In contrast to the 'hard' limits on the maximum allowable actuator velocity and acceleration (which are neglected in this paper), this restriction is a 'soft' limit. Whilst electro-mechanical actuators may be employed to implement the discrete actuation systems considered here, owing to the large accelerations associated with the necessarily abrupt changes in velocity and consequent heating effects for electro-mechanical designs, hydraulic designs may, in general, be more appropriate. Unfortunately, whilst in hydraulic actuator designs the 'hard' limits on the actuator velocity and acceleration are well known, the 'soft' restrictions on the allowable actuator operation appear to be less well understood. This hinders a fair comparison between different control strategies. The approach adopted in this paper is, therefore, to design the controllers to respect the operating restrictions of the continuous actuation system (electro-mechanical). The corresponding demands which these controllers place on the discrete actuation system are then compared using the standard deviation of the pitch velocity and of the pitch acceleration as approximate metrics.

To determine the closed-loop stability with the actuator configuration of figure 1b it is necessary to re-formulate the control loop so that the actuator nonlinearity lies in the feedback path. This gives the forward path transfer function $20K(1+G(s))/s(s+20)$, where $G(s)$ is the combined plant and controller transfer function (omitting the actuator). With the conventional linear controller, the Nyquist plot of this transfer function is shown in figure 2. Owing to the low-frequency real-axis crossing to the left of the (-1,0) point, the Nyquist curve intersects the inverse of the describing function of the nonlinearity indicating the existence of a limit cycle. The existence of a limit cycle is confirmed by simulation and, intuitively, is the result of the quantisation of the positions which the blade pitch angle may take up with this actuator configuration. In view of this explanation, it is likely that the limit cycling characteristic is not confined to the particular controller and wind turbine considered here and the actuator configuration of figure 1a is, therefore, preferred to that of figure 1b.

4. TRANSITION FROM BELOW TO ABOVE RATED OPERATION

Below a certain 'rated wind speed', the power generated is less than the turbine rating and no control action is required. However, when the wind speed rises above rated, the power output is regulated at the rated value of the turbine, 'rated power', by suitably adjusting the pitch angle of the rotor blades. Hence, it is necessary to automatically start-up and shut-down the controller as the wind speed fluctuates. The controller has integral action to ensure rejection of steady wind disturbances and suitable low frequency shaping (Leithead *et al.* 1991) to ensure rejection of gusts (ramp-like increases or decreases in wind speed which persist over several seconds). Consequently, controller start-up requires to be treated with some care to avoid prolonged transients and minimise the loads on the wind turbine.

A common approach to controller start-up is to simply freeze the controller integral action when below rated operation is detected; that is, when the demanded pitch angle of the turbine blades falls below a specified threshold value (zero degrees here), the accumulation sum in the integral calculation is suspended. However, this approach is not always effective in preventing large start-up transients. Intuitively, whilst this approach prevents the pure integrator in the controller from adopting an inappropriate state during below-rated operation, it does not cater for the low frequency pole in the controller with which the prolonged start-up transients are associated. Leithead *et al.* (1991) propose an alternative start-up technique whereby the controller is partitioned such that the slow dynamics are contained in C_{inner} and the fast dynamics are contained in C_{outer}. A minor feedback loop is introduced within the controller, around C_{inner}, which mimics the action of the physical wind turbine and switches in to permit the controller to continue operating below rated wind speed (equivalent to a negative pitch angle demand). The start-up transients may be substantially reduced with this strategy.

However, this start-up approach cannot be directly applied with the discrete actuator configuration of figure 1a since the integral action of the control system is provided by the actuator rather than by a pure integrator within the controller itself. The output of the actuator is constrained to be positive and the physical realisation of the integral action ensures that the integrator automatically has the correct initial value at the transition from below to above rated operation. However, as noted above, it is also necessary to cater for the low frequency pole in the controller with which the prolonged start-up transients are associated. With the conventional linear control strategy, this may be achieved by employing a minor loop with a pure integrator in the feedback path as depicted in figure 3. During above rated operation, the feedback *via* gain K ensures that the output of this pure integrator follows the actuator output. An appropriate value for the gain K is determined to be 20. It is straightforward to extend this approach to accommodate the dual-mode and augmented dual-mode control strategies.

5. PERFORMANCE ASSESSMENT

The impact upon performance of adopting an actuator with the configuration depicted in figure 1a is assessed by performing simulation tests to compare the probability distribution of the power output for the dual-mode and augmented dual-mode controllers. Owing to lack of space, only a brief summary of the results is presented. One of the main requirements is to reduce fatigue damage, the level of which is strongly dependent on the peak loads experienced. The probability distributions for the two controllers are shown in figure 4 for a mean wind speed of 24 m/s and a nominal turbulence intensity of 20%. In comparison to operation with the continuous actuator, performance is degraded with the discrete actuator. The power probability distribution for the dual-mode controller with the discrete actuator is similar to that for the linear controller with the continuous actuator, having a peak power output of around 550 kW. The power distribution for the augmented dual-mode controller with the discrete actuator is similar to that for dual-mode controller with the continuous actuator (not shown here owing to lack of space, see Leith & Leithead 1996), having a peak power output of around 500 kW; that is, around 50kW less than with the unaugmented dual-mode controller.

Whilst the standard deviation of pitch acceleration is a useful measure of the actuator utilisation for an electro-mechanical actuator, it is unclear which type of quantity might be employed as a similar indicator for a hydraulic actuator. Nevertheless, for comparison it is noted that for the discrete actuator the standard deviation of the actuator acceleration is 22.4 deg/s^2 and 25.56 deg/s^2 for the dual-mode and augmented dual-mode controllers, respectively, and the standard deviation of actuator velocity is 1.88 deg/s and 2.45 deg/s, respectively (for a mean wind speed of 24 m/s and nominal turbulence intensity of 20 %). Hence, based on these metrics, these control strategies make similar demands on the actuation system.

6. CONCLUSIONS

In comparison with continuously acting actuation systems, the restriction to discrete actuator motion can degrade stability margins and, indeed, lead to instability. Consequently, it is necessary to re-configure controllers, designed for use with a continuous actuator, for operation with a discrete actuator. In addition, a novel approach is proposed for achieving a smooth transition between below and above rated operation despite the discontinuous nature of the actuation system.

The performance of a dual-mode controller with the discrete actuator is similar to that for a conventional linear controller with the continuous actuator; whilst the performance for an augmented dual-mode controller with the discrete actuator is similar to that for the dual-mode controller with the continuous actuator. Hence, as might be expected, performance, in comparison to the continuous actuator, is degraded somewhat with the discrete actuator. However, by adopting a more sophisticated control strategy the performance degradation may be alleviated.

ACKNOWLEDGEMENTS

The support of the EPSRC, DTI (formerly D.En) and ETSU, by whose permission this paper is published, is gratefully acknowledged..

REFERENCES

AGIUS, P.R.D., ANDERSON, C.G., GREEN, D.R.R., SMITH, W.M.R., URWIN, N.J., 1993, Machine for the Nineties. Report by Windharvester Ltd. under DTI Contract No. E/5A/6110/2874.

ATHERTON, DP, 1982, *Nonlinear Control Engineering* (New York: Van Nostrand Reinhold).

LEITH, D.J., LEITHEAD,W.E., 1995, Directly Responding to Peak Power Excursions in Pitch-Regulated HAWTs. *Proc. BWEA Conf.*; 1996, Performance Enhancement of Wind Turbine Power Regulation by Switched Linear

Control. *Int. J. Control*, **65**, 555-572; 1997, Implementation of Wind Turbine Controllers. *Int. J. Control.*, **66**, 349-280.

LEITHEAD, W.E., DE LA SALLE, S.A., REARDON, D.L., GRIMBLE, M.J., 1991, Wind Turbine Control Systems Modelling and Design. DTI Rep. ETSU WN5108.

MERRIT, H.E., 1967, Hydraulic Control Systems. *John Wiley & Sons*, New York.

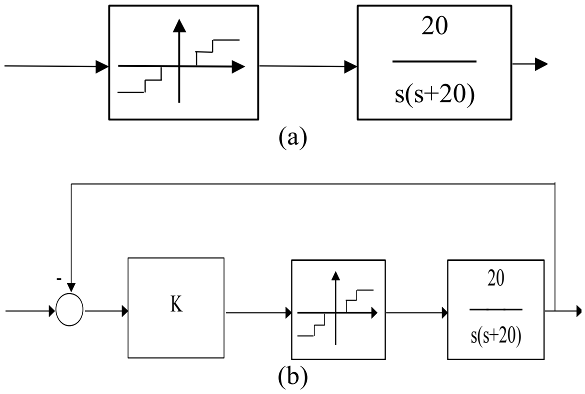

Fig. 1 Discrete actuator configurations

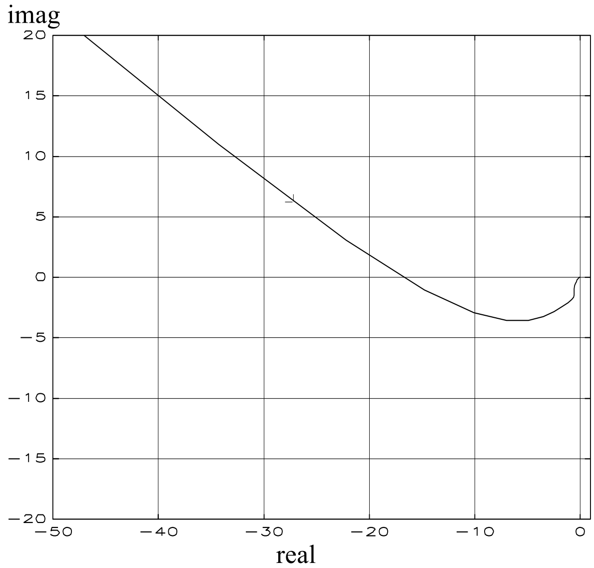

Fig 2 Nyquist plot of forward path transfer function

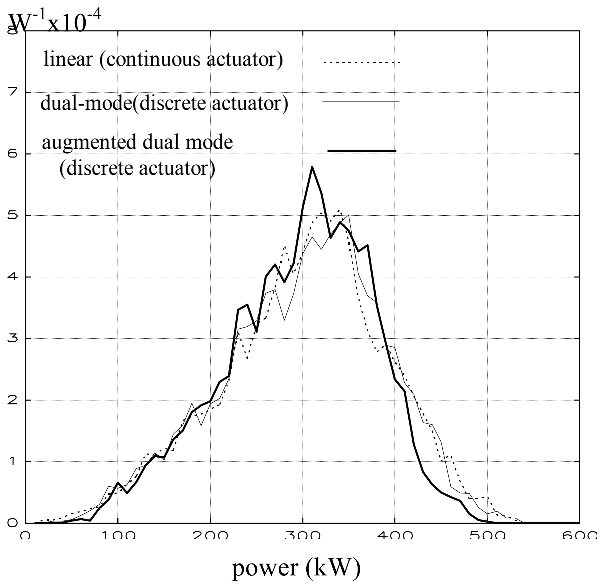

Fig 4 Probability density function of power
(24 m/s wind, 20% turbulence intensity TI)

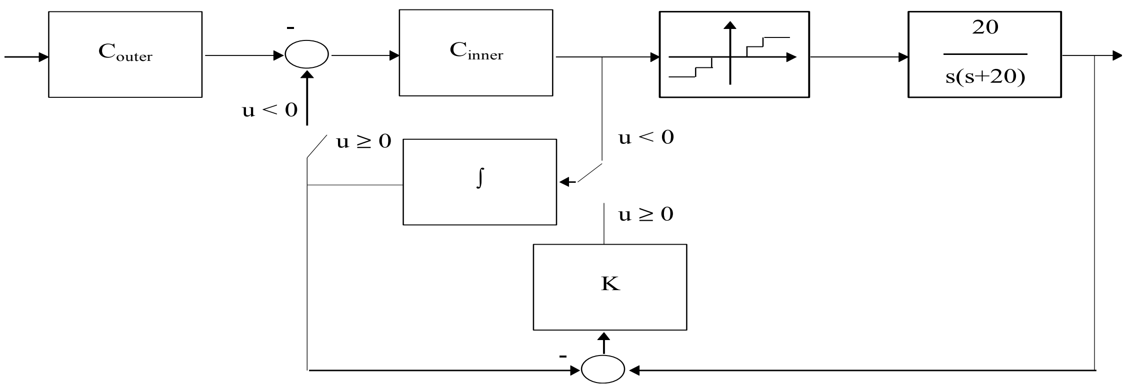

Fig 3 Arrangement employed for switching between below and above rated operation